

JKSimFloat V6: improving flotation circuit performance and understanding

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ABSTRACT: Methods of analysing and optimising flotation circuits have improved significantly over the last 15 years. Mineral flotation is now generally better understood through major advances in measuring and modelling the sub-processes within the flotation system. JKSimFloat V6 is a user-friendly Windows-based software package incorporating simulation, mass balancing, and, currently under development, liberation data viewing and model fitting. This paper presents an overview of the development of the program up to its current status, and the plans established for the future. The application of the simulator, in particular, at various operations is also discussed with emphasis on the use of the program in improving flotation circuit performance.

1 INTRODUCTION

While the practice of froth flotation has been in existence for over 100 years, many aspects are still considered as ‘black magic’. Researchers for many decades have attempted to model the flotation process in an effort to better understand, control and improve the performance. These models have ranged from fully empirical, ‘black box’ approaches, through to the more fundamental investigations of single bubble-particle interactions.

The simple, empirical models are generally easy to generate the necessary data, but the capability of predicting performance when some part of the process has changes is often lacking. The more detailed, fundamental models often predict the performance reasonably accurately, but it is generally difficult to obtain all the parameters necessary, and often some are fitted by empirical relationships.

JKSimFloat incorporates the modelling methodology developed as part of the Australian Minerals Industry Research Association (AMIRA) P9 project, titled ‘The Optimisation of Mineral Processes by Modelling and Simulation’. This is a collaborative research project involving the Julius Kruttschnitt Mineral Research Centre (JKMRC) in Australia, the University of Cape Town (UCT) in South Africa and McGill University of Canada. This methodology uses data obtained from the flotation plant and incorporates various semi-

empirical sub-process models to represent the data for simulations.

This paper presents a brief overview of the models used in JKSimFloat, as well as a chronological development of the program. A more detailed discussion of the models and equations used in JKSimFloat has been given previously in Harris et al (2002); this current paper aims to include the early research as well as to update the development process of the program and describe several case studies.

2 JKSIMFLOAT 1990-1994

Following the success of the development of JKSimMet (McKee & Napier-Munn, 1990), in the early 1990’s a decision was made to incorporate the then new flotation models into a simulator. The models were at this time contained in complex programming that were not often used by metallurgists on flotation plants, however it was recognised that there was great value to be gained in using the models for simulations.

These models were the pre-cursor to the current models, with the factors affecting the recovery of mineral particles divided into two groups – machine factors and mineral properties (or floatability).

The floatability of the ore was defined by the average floatability of each mineral-size class and the proportion of the floating material. This concept is still used today and expanded to as many size

fractions, minerals and floatability components as required.

The effects of machine parameters for conventional flotation cells were determined using the following equation:

$$R_{i,j,k} = \frac{k_{i,j,k}\tau}{1 + k_{i,j,k}\tau} + R_w \exp(-ENT \cdot d_p) \quad (1)$$

where $R_{i,j,k}$ – recovery of the k^{th} floatability fraction from the i^{th} size and the j^{th} mineral fraction,

$k_{i,j,k}$ – rate parameter (min^{-1})

τ – cell residence time (min)

R_w – water recovery (-)

ENT – entrainment factor (cm^{-1})

d_p – mean particle size (cm)

The rate parameter was assumed to be equivalent to the component floatability, corrected by a scaling factor as follows:

$$k_{i,j,k} = \frac{C_{i,j,k}}{100} \quad (2)$$

where $C_{i,j,k}$ – floatability of the i^{th} , j^{th} and k^{th} fraction, and was fitted within the software program.

A significant amount of research was conducted at the JKMRRC around this time involving modelling of flotation columns (Alford, 1990, Alford et al, 1991, Alford 1992). This research was incorporated into JKSimFloat and used a single phase model to describe the recovery of the column. The recovery across the pulp phase was determined to be a function of a first order rate parameter and a residence time distribution (from Alford, 1992); the actual form of the equation was dependent on the mixing regime:

$$R_{pulp} = f(k_{i,j,k}, \tau_{i,j}, \sigma_{i,j}) \quad (3)$$

where $k_{i,j,k}$ – first order rate parameter, incorporating froth phase effects (min^{-1}),

$\tau_{i,j}$ – mean particle residence time (min),

$\sigma_{i,j}$ = variance in the residence times about the mean (-).

JKSimFloat was released in 1993 as a MS-DOS program and was found to be successful in predicting flotation circuit performance over a wide range of operating conditions. However, the rate parameter was limited to a global parameter and did not relate to different operating regimes.

3 FLOTATION RESEARCH 1994-2000

As part of the AMIRA P9 project, attention was focussed on understanding the various sub-processes within the flotation system. The recovery of particles was split into both true flotation (particles

attached to bubbles) and entrainment (particles entrained between bubbles), to give the overall recovery equation for a particular component (from Savassi, 1998):

$$R_i = \frac{P_i \cdot S_b \cdot R_f \cdot \tau \cdot (1 - R_w) + ENT \cdot R_w}{(1 + P_i \cdot S_b \cdot R_f \cdot \tau)(1 - R_w) + ENT \cdot R_w} \quad (4)$$

where P_i – ore floatability for component i ,

S_b – bubble surface area flux (min^{-1})

R_f – froth recovery

τ – residence time (min)

R_w – water recovery (-)

ENT – degree of entrainment (-)

The overall recovery for a feed with n classes of similar particles is then given by:

$$R = \sum_{i=1}^n m_i R_i \quad (5)$$

where m_i is the mass fraction of particle class i in the feed.

The methodology to obtain parameters used in the model has been described in detail elsewhere (Alexander et al, 2000). The following is a brief description of the parameters used in the model:

- gas dispersion, i.e. bubble surface area flux
- froth recovery
- entrainment
- ore floatability

3.1 Gas dispersion parameters

Gas dispersion in the pulp phase of a flotation cell can be characterised by the bubble surface area flux, S_b . Bubble surface area flux is defined as (Gorain et al, 1997):

$$S_b = \frac{6J_g}{d_b} \quad (6)$$

where J_g – superficial gas velocity (m/s)

d_b – Sauter mean bubble diameter (m)

The superficial gas velocity (J_g) is measured using a J_g probe. The measurement procedure for this device is described elsewhere (Gorain et al, 1996, Power et al, 2000). The bubble size can be measured using either the UCT bubble size analyser (Tucker et al, 1994) or the McGill bubble viewer (Chen et al, 2001). A database of these measurements from industrial flotation cells has been developed from studies around the world (Schwarz & Alexander, 2005), which continues to grow at a rapid rate.

3.2 Froth recovery

There are various techniques focussed on measuring the froth recovery within industrial flotation cells. These ranged from changing the froth heights and extrapolating the linear relationship between the flotation rate constant and froth height (Vera et al, 1999), to performing mass balances across the froth phase (Savassi et al, 1998, Alexander et al, 2003). In general, the froth recovery of a flotation cell can be defined as:

$$R_f = \frac{\text{flowrate attached particles in concentrate}}{\text{flowrate attached particles reporting to froth}} \quad (7)$$

Relationships have been developed to predict froth recovery based on changes in operating conditions (Gorain et al, 1998, Mathe et al, 2000), however more research is continuing in this area.

3.3 Entrainment

The contribution of entrained particles to the overall recovery and grade of a system is critical. Techniques were developed within the AMIRA P9 project to collect the entrained solids from regions just below the pulp-froth interface. Additional methods were developed to describe the entrainment response from empirical relationships (Savassi et al, 1998, Savassi et al, 1999). The degree of entrainment is defined as:

$$ENT = \frac{R_{\text{entrainment}}}{R_{\text{water}}} \quad (8)$$

where $R_{\text{entrainment}}$ is the recovery of the entrained material.

In general, the recovery of entrained material is obtained from mass balanced data, using a liberated gangue mineral as a tracer. This method is well described by Savassi et al (1998).

3.4 Ore floatability

A methodology to obtain the floatability parameters (P and m) was proposed by a number of authors (Harris et al, 1997, Runge et al, 1997, Alexander & Morrison, 1998). The main concept of this methodology involves separating particles of similar floatabilities into components, with an average floatability rate, as suggested by Imaizumi & Inoue (1965). These components are assumed to adequately describe the floatability distribution of a mineral entering a flotation circuit. A non-linear optimisation procedure was used to determine the number and value of these floatability components (Harris et al, 1997), and a later methodology to linearise the regression procedure to enable easier

solutions and higher confidence levels was developed (Alexander & Morrison, 1998). The use of batch test data to include in the model fitting routine was also implemented, with the concept of 'nodal analysis' introduced (Runge et al, 1997).

Nodal analysis involves taking samples of streams from the plant and floating them immediately in the laboratory. Using the recovery-time profiles and re-combining them according to the mass flowrates of minerals in the streams, the analysis shows if floatability has been conserved or changed around that particular node. If floatability is conserved around the whole circuit in question, the assumption of the same P values throughout the circuit is validated. Nodal analysis is also useful for diagnosing how effective various floatability changing processes are, such as regrinding and reagent addition, see Figure 1.

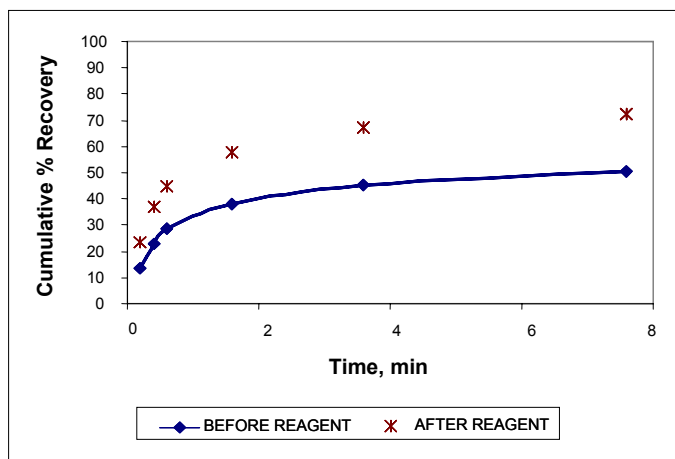


Figure 1. Recovery-time profiles using nodal analysis to determine effect of reagent on particle floatability

4 JKSIMFLOAT 2000-PRESENT

During the development of the new flotation models discussed previously, it was noted that the structure of the MS-DOS version of JKSimFloat did not allow these to be incorporated. There was also a shift towards Windows-based programs around this time. In 2000, it was determined that JKSimFloat should be re-designed in a Windows environment, with the capability to incorporate these models and future models from the AMIRA P9 project. A user group was established involving personnel from research, consulting, computing and mathematics at the JKMC and UCT. This user group developed a detailed specification incorporating the means to transfer technology to industry in a user-friendly environment, as well as enabling the research team to continue to test and develop new models. The development of JKSimFloat V6 is a staged process – simulation, mass balancing, liberation data viewing and model fitting. The funding for the first stage of

development came from the Queensland Government and a sub-group of AMIRA P9 sponsors. JKMRRC and JKTech also provided significant funding for the project. The development was administered by AMIRA, and known as P868.

4.1 *JKSimFloat simulating*

In 2001 the detailed specification of the underlying structure was finalised, allowing as many different size fractions, minerals and floatability components as required to be used in a highly flexible stream structure. Programming in C++ commenced in 2002. The first version of JKSimFloat V6.0 was released in 2003, which included the graphical user interface and simulator module. Sponsors of the AMIRA P868 project had the option of a pre-configured simulator, using the methodology discussed previously to obtain the parameters, or to implement their own models within the software program. This version was tested against other spreadsheet-based simulators and found to be significantly faster, while generating similar results. However, a need for more convenient data display was identified.

Specifications for new overview screens and equipment managers were written during the latter part of 2003 with V6.1 released in 2004. Feedback from the sites using the program also indicated the flowsheet drawer was not very user-friendly, and this was again specified in detail, with the release of V6.1^{PLUS} in 2005. The release of the program was initially restricted to companies who were involved in funding the project, with the sale of the program possible to other AMIRA P9 sponsors in June 2005, and other companies from June 2006. Many companies around the world are now using the program to conduct simulations to better understand and optimise their flotation circuits with some of these cases discussed later in this paper.

4.2 *JKSimFloat mass balancing*

The second phase of JKSimFloat development included the incorporation of a mass balancing algorithm developed at the JKMRRC, which enables balancing on both an overall basis and a size-by-assay basis. This mass balancing algorithm is essentially a minimisation of sum of squares with multi-linear constraints. This corresponds to a common set of mathematical problems generally described as the 'quadratic problem'.

The algorithm is based on a Quasi-Newton approach which means that the errors in the constraints are used to determine the changes required in calculated variables, with the amount of movement of the calculated variables controlled by the standard deviations of the experimental values.

Hence standard deviation values of 0 mean that a calculated value will equal the experimental value

and will not change. If all the standard deviations are near 0, the program will not have enough freedom to find a solution, and therefore will not converge. The JKSimFloat standard deviation interface provides formulae to allow appropriate standard deviation values to be set.

Specifications for the mass balancing and incorporation of the algorithm into the code were performed in 2004 with the testing, debugging and release of V6.2 in 2005.

A need for a more flexible interface to the mass balance algorithm, which allowed parts of the circuit to be held constant while other parts were balanced, was identified. Specifications were written at the end of 2005 to include the ability to identify streams as major, minor or missing, with the capability of fixing or balancing these streams, especially with a large number of missing data. Programming for this stage is currently underway, with the release of V6.2^{PLUS} expected in 2006.

4.3 *JKSimFloat liberation data viewing*

Many of the new models being developed in the AMIRA P9 project are using a 'property-based' modelling approach, highly dependent on mineral liberation characteristics. JKSimFloat was designed to enable liberation data from either the JKMRRC Mineral Liberation Analyser (MLA) (described in Gu, 2003) or the CSIRO QEM*SCAN (described in Gottlieb et al, 2000) systems to be imported and viewed within the program. This data will then be able to be used in the property-based models, and be mass balanced on a size by assay by liberation basis in the future.

This stage was specified in great detail with over 80 screens available for the user to investigate how the liberation characteristics change throughout a flotation circuit, provided liberation data is available for these streams. Programming of V6.3 commenced in 2005, and an alpha version was available at the end of 2005. Priorities of the development were changed to reflect the user requirements, and the final stages of programming this version was delayed to focus on the enhancements to the mass balancer (V6.2^{PLUS}) and model fitting. It is envisaged that liberation data viewing will be continued after these stages have been completed.

4.4 *JKSimFloat model fitting*

The next phase of development will include model fitting within the JKSimFloat package. Currently the determination of the model parameters is performed in a spreadsheet, involving complex formulae. This is generally very time consuming and potentially prone to error. As more companies are becoming skilled in developing models, there has been a requirement to standardise the fitting

routines. The ability to use JKSimFloat to fit the model parameters will greatly increase the efficiency and level of confidence in developing the models; although it is envisaged that a high degree of training will still be required.

Specifications are currently being finalised and programming of V6.4 is anticipated to commence mid-2006, with the release in mid-2007.

5 CASE STUDIES

5.1 Case study 1

The first circuit to be tested using the previous spreadsheet-based simulation tools and the new simulation module in JKSimFloat V6.0 showed a remarkable increase in simulation speed. The circuit in question was from a base metals plant, and is shown in Figure 2.

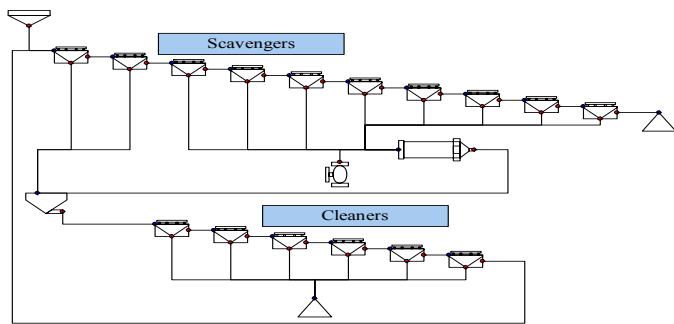


Figure 2. Flowsheet of part of a base metals circuit used to test JKSimFloat V6.0 simulation module

Simulations conducted included:

- increasing the air flowrate in selected cells
- open circuiting the cleaner tails
- increasing the number of cells in the scavenger section
- increasing the number of cells in the cleaner section

Each of these simulations took less than 1 minute to complete using JKSimFloat, compared with about 30 minutes using the spreadsheet-based simulator. The company in question has been using JKSimFloat in its current state for several simulation scenarios and have found it useful in planning and optimisation studies.

5.2 Case study 2

The second case study was conducted in a gold plant, and involved the whole flotation circuit, as shown in Figure 3.

The simulations conducted using JKSimFloat V6.1 included:

- increasing water addition to the recleaners
- recycling the concentrate from the second stage of cleaning

- further cleaning of the concentrate from the first stage of mechanical cells
- extra capacity in the recleaner bank

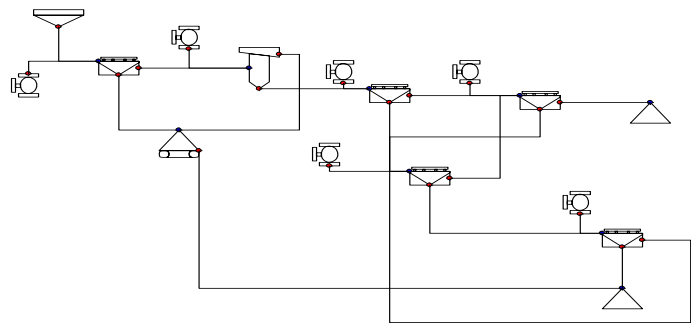


Figure 3. Flowsheet of circuit used in Case Study 2

Results of the simulations and the other analysis performed as part of this study enabled the site to identify problem areas throughout the circuit. These included operating certain cells at higher air rates, ensuring the cleaner feed is kept at a particular solids density and changes to the control system. Using the results from this study produced a 1.3% increase in gold recovery with a substantial decrease in operating costs. The benefits from this study have resulted in a reported US\$1.3 million a year improvement to the mine (Alexander et al, 2005).

6 CONCLUSIONS

JKSimFloat has been developed to provide metallurgists and researchers a tool to better understand and optimise their flotation circuits. The development of the software program has followed the research outcomes of the AMIRA P9 project. This methodology has been found to be highly useful for plant metallurgists, researchers and consultants alike.

The current state of the software package includes simulation and size-by-assay mass balancing modules. Plans are already established to extend the program and include liberation data viewing and model fitting for a complete flotation circuit analysis package.

As more research continues in the flotation system, JKSimFloat will also continue to develop and be a useful tool to test these new models in a user-friendly environment.

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